LA-UR-12-26474

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Title: Electromagnetic Pulses from Hypervelocity Meteoroid Particle Impacts (HMPI) on Spacecraft

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Electromagnetic Pulses from Hypervelocity Meteoroid Particle Impacts (HMPI) on Spacecraft

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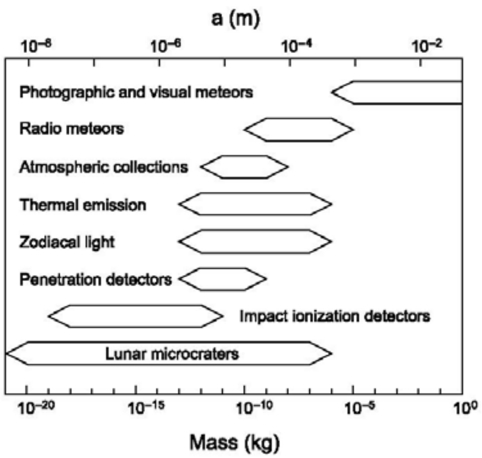
Growing threats to Spacecraft

- Massive increase in space debris
  - Problem will worsen over time, barring remediation
  - but it is being thought about…

  e.g. *International Interdisciplinary Congress on Space Debris Remediation,* Montreal 2011

- Incomplete understanding of natural meteoroid flux
  - Characterization efforts well established, but more work needed.
  - Variety of modalities used
  - Meteoroid speeds: 60 km/s (mode)

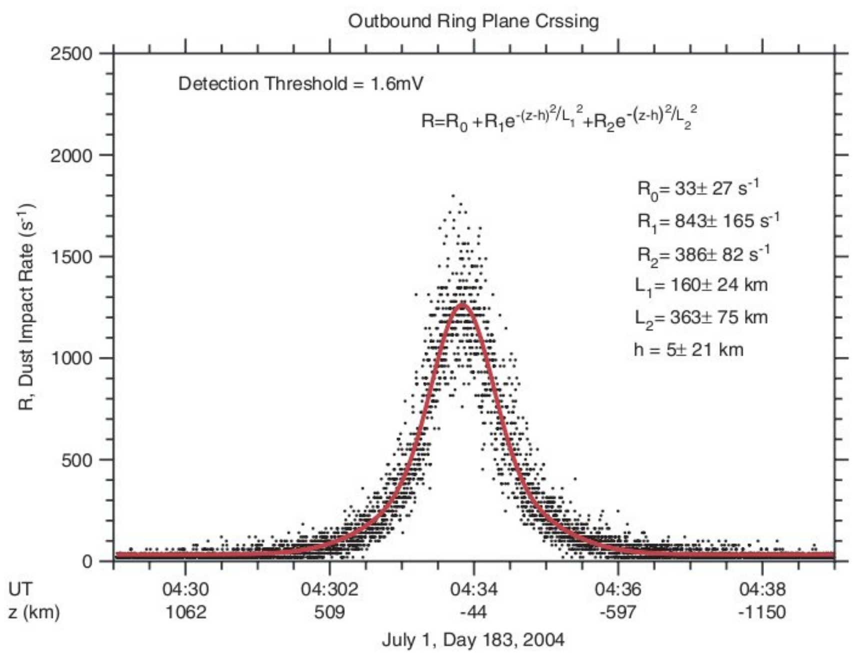


- Increase in complexity of satellite systems

The HMPI Threat

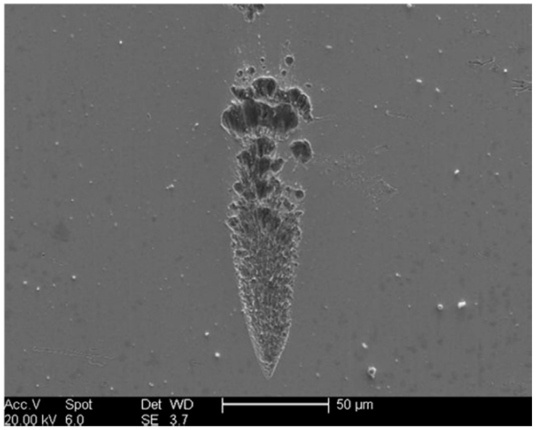
- How Often?
  - Based on radar measurements, meteoroid impacts imparting ~ 1 J should occur on a 10 m^2 about once per hour *continuously*
- How Bad?
  - Mechanical damage is minimal, but *electrical* damage may be significant electromagnetic impulses (EMP)
  - Spacecraft charging may play a role as well
  - Particles and charging can act together

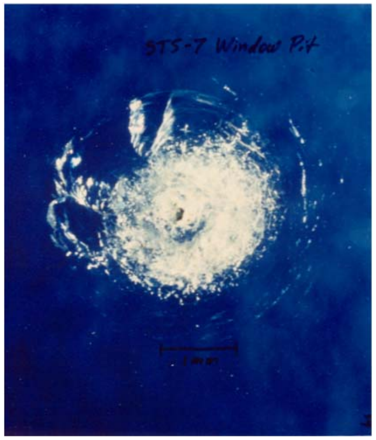
HMPI Direct Measurement: Cassini Detection of Dust Impacts

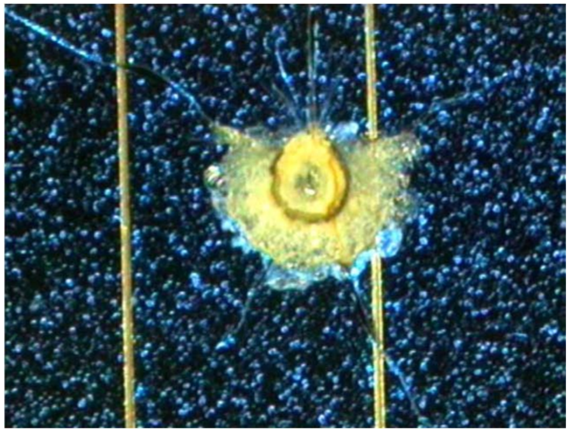


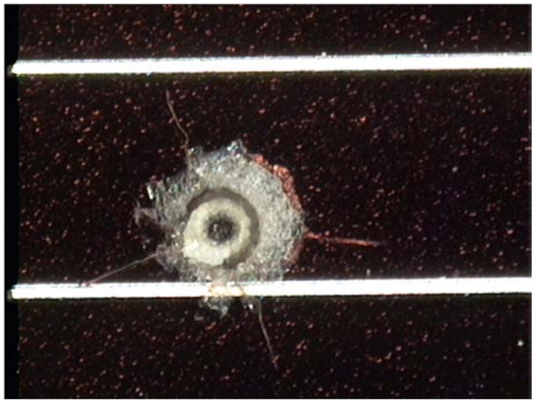
Micro-crater Observations on Hubble ST Solar Cells

Drohlshagen, Adv. Sp. Res., 2008





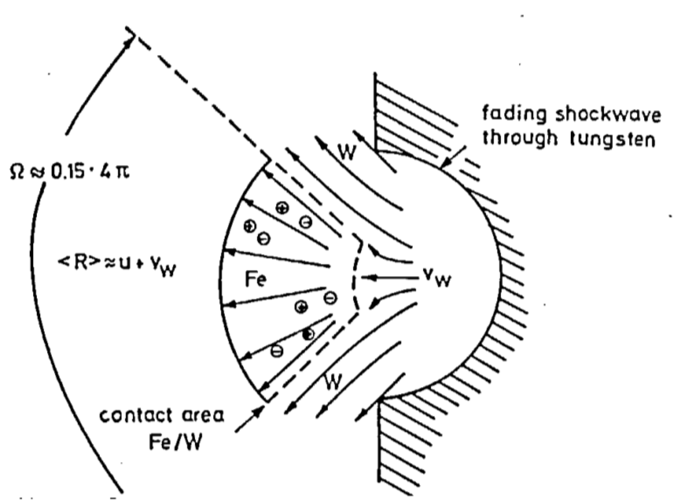


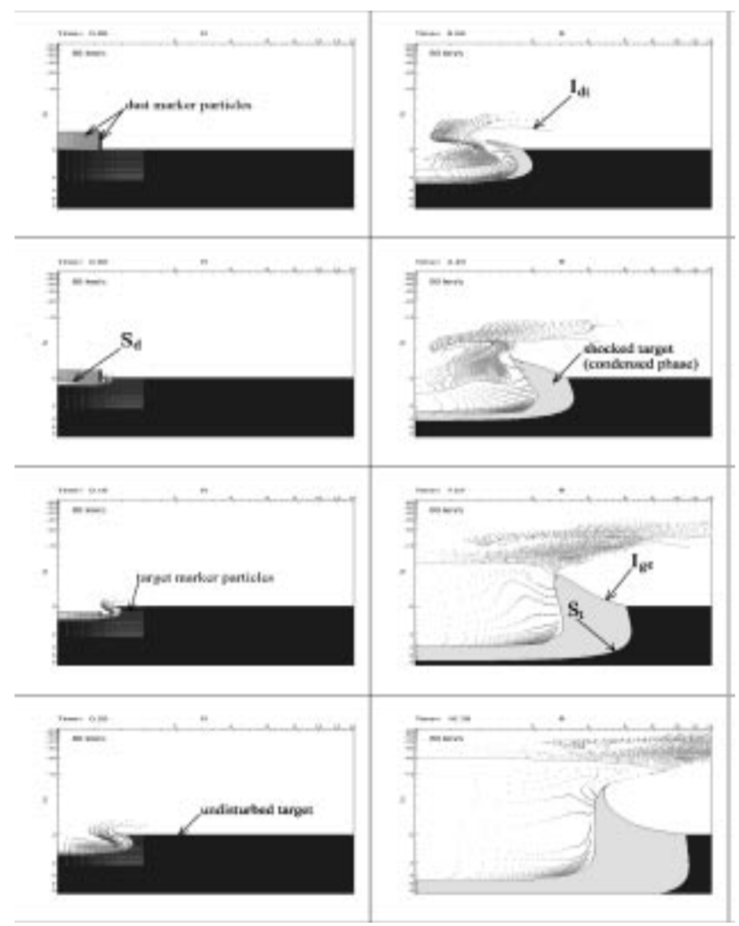


Modeling Efforts indicate Shock Formation

Hornung, Astro. Sp. Sci, 2000

Drapatz and Michel,
Z. Naturforsch., 1974

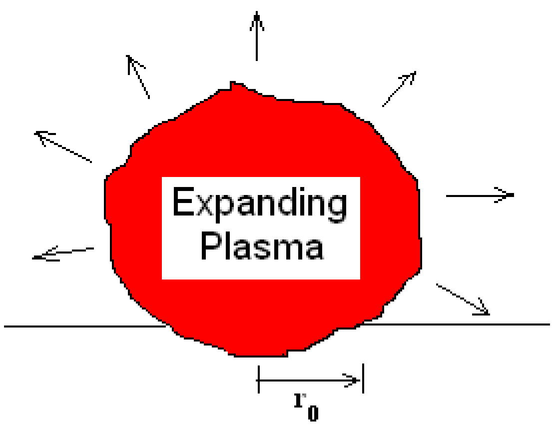




How do we Estimate the EMP?

Plasma oscillations:

dipole moment due
to ground plane



Other Mechanisms:

Bremsstrahlung emission:
small at expected
temperatures

Direct charge transfer:
slow development
uncertain convection
process

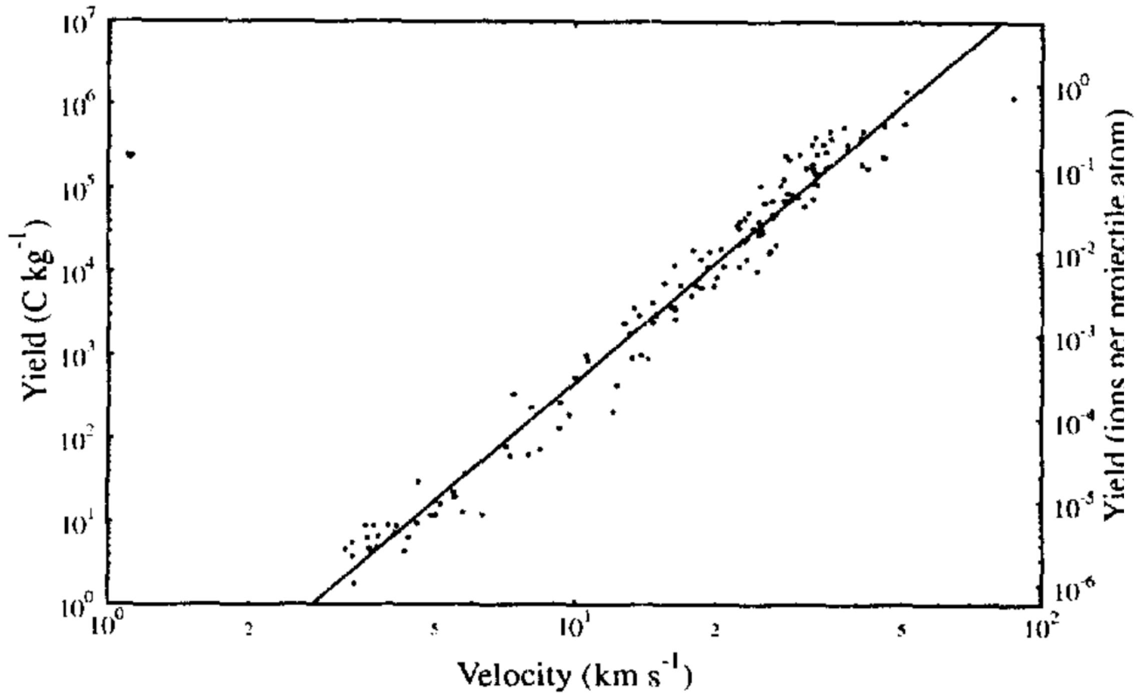
Electrostatic discharges:
requires electron flux
depends on device
capacitance

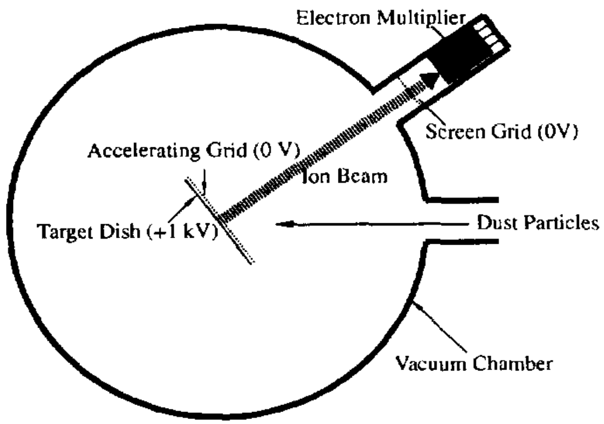
Critical parameters:

Crater size: determines initial plasma density

Meteoroid energy: determines initial impulse strength

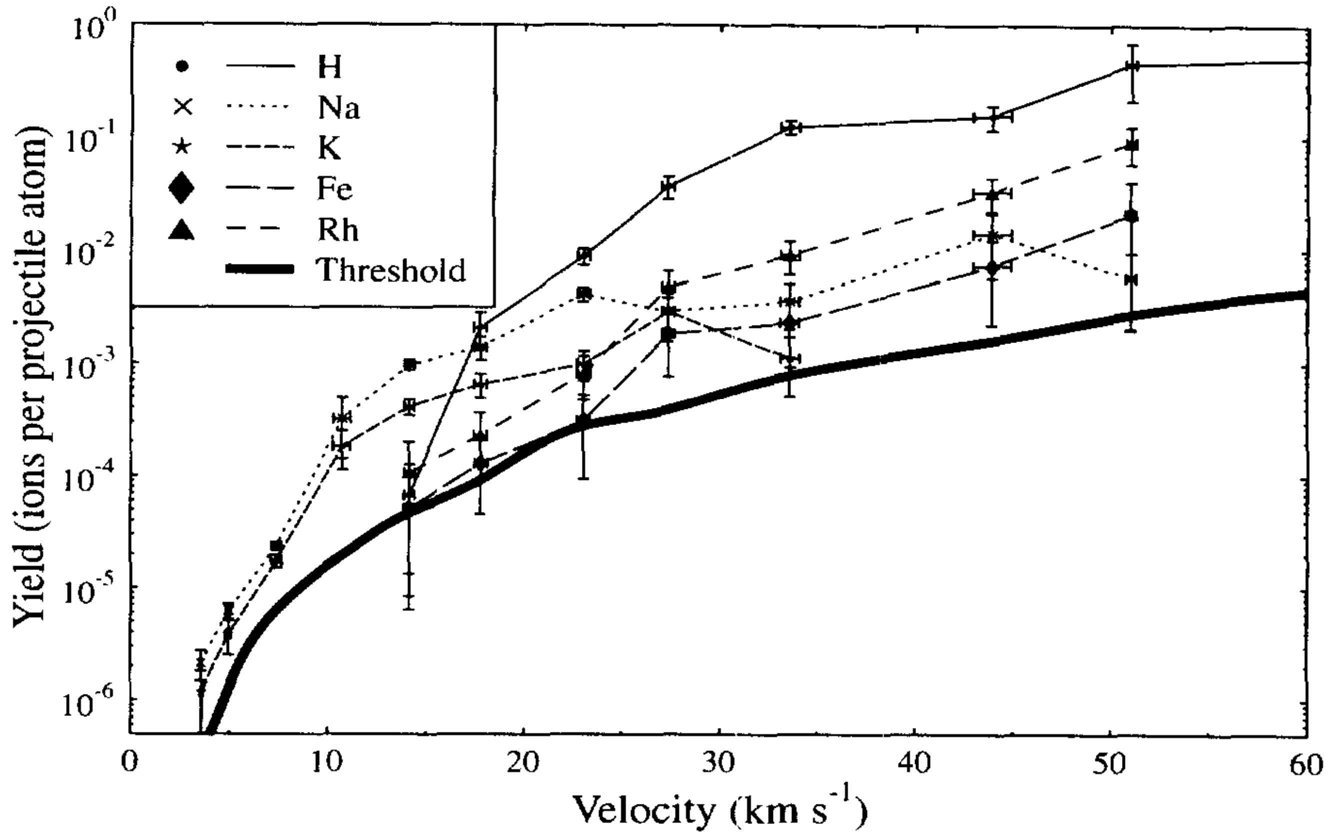
Plasma Production from Dust Acceleration





Ref: Ratliffe, et. al., Int. J. Impact Engineering, 20, p. 663, (1997)

Ion Yields from Dust Acceleration



Ref: Ratliffe, et. al., Int. J. Impact Engineering, 20, p. 663, (1997)

Empirical Measurements to Date

$$q = 0.1m\left(\frac{m}{10^{-11}}\right)^{0.02}\left(\frac{v}{5}\right)^{3.48}$$

Charge released

$$r_o = (k)(m^{0.352})(\delta^{1.167})(v\cos\vartheta)^{0.667}$$

Crater size

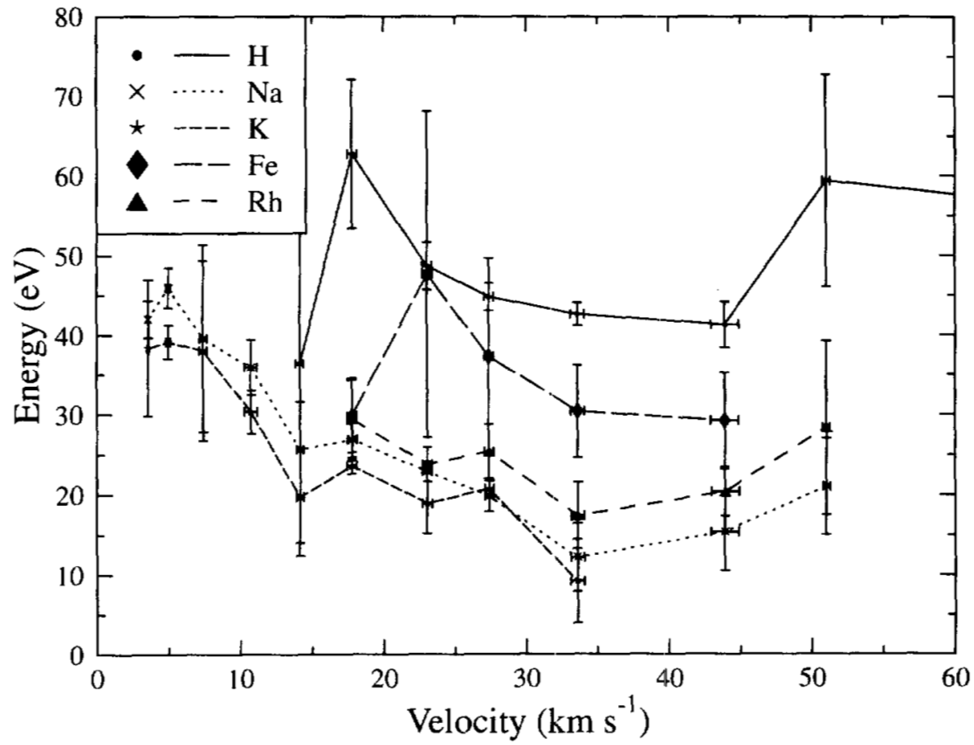
$\Rightarrow$ Electron density > 10^{19} cm^{-3} ! ($\omega_{p,0}$ ~ 10^{15} Hz)

But what is the expansion rate ?

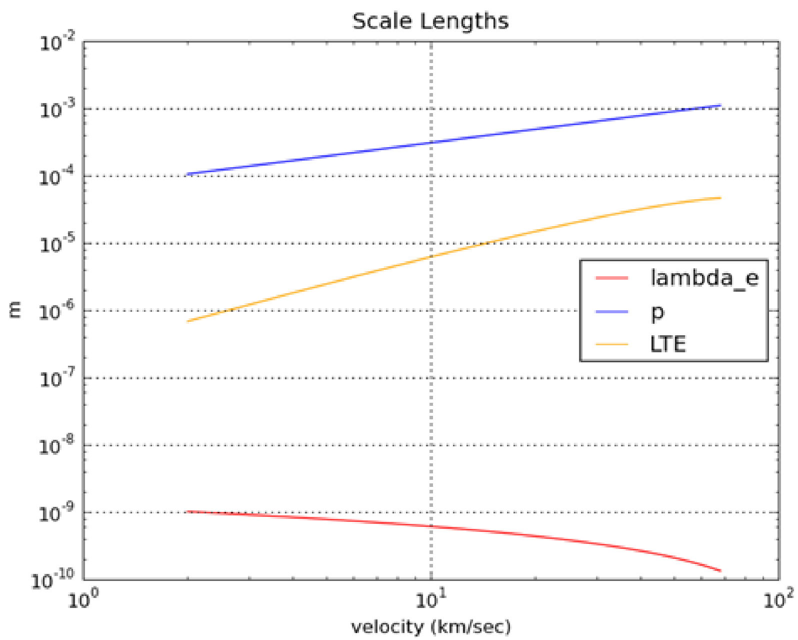
Expansion Rate

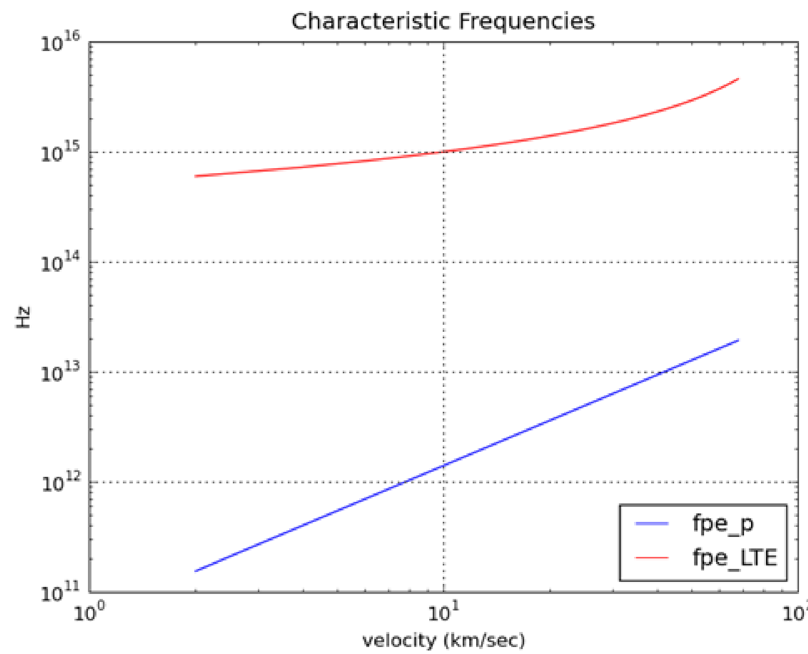
Assume the electrons and ions are initially in equilibrium.

Ratcliffe, Int. J. Impact Engin,1997



Characteristic Scales





Plasma Expansion

Assume a density Evolution of the form: $$n_e(t) = \frac{n_{e,o}}{\left(1+{}^{2c_s t}\!/_{r_o}\right)^3}$$

with the expansion velocity: $$c_s = \sqrt{\frac{\gamma kT}{m}}$$

Dynamical equation:

$$\boxed{\ddot{\xi}(t) = -\frac{e^2 n_e \xi(t)}{m_e \varepsilon_o} = -\frac{\omega_{p,o}{}^2 \xi(t)}{\left(1+{}^{2c_s t}\!/_{r_o}\right)^3}}$$

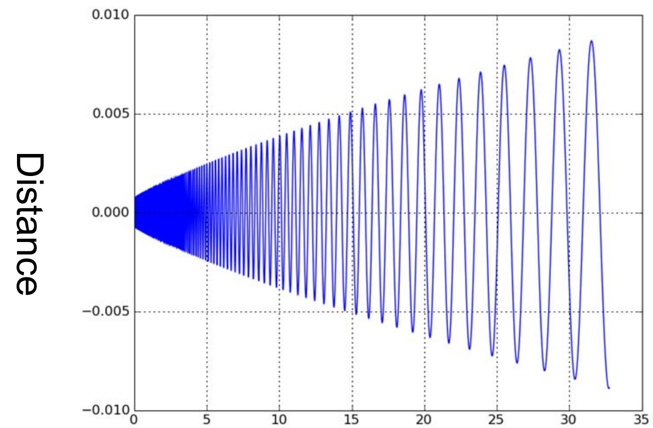
which has the WKB solution:

$$\xi(t) = -\frac{v_{th,e}}{\omega_{p,o}}\left(1+\frac{2c_s t}{r_0}\right)^{3/4} \sin\left(\omega_{p,o}\frac{r_0}{c_s}\left[1+\frac{2c_s t}{r_0}\right]^{-1/2}\right)$$

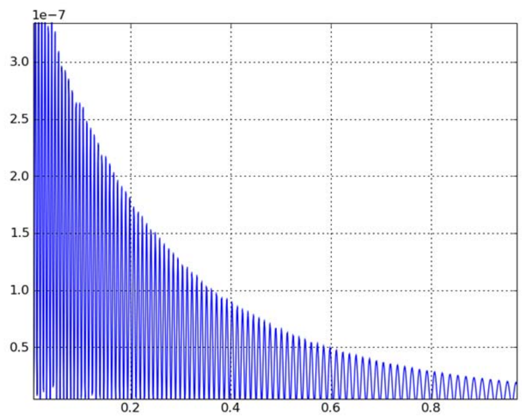
Radiation Mechanisms

$$P = \frac{\omega_{p,o}^4 \left(\frac{v_{th,e}}{\omega_{p,o}}\right)^2 e^2 N \sin^2\left(\omega_{p,o}\frac{r_0}{c_s}\left[1+\frac{2c_s t}{r_0}\right]^{-1/2}\right)}{6\pi e_0 c^3 \left(1+\frac{c_s t}{r_0}\right)^{9/2}}$$

Larmor Formula

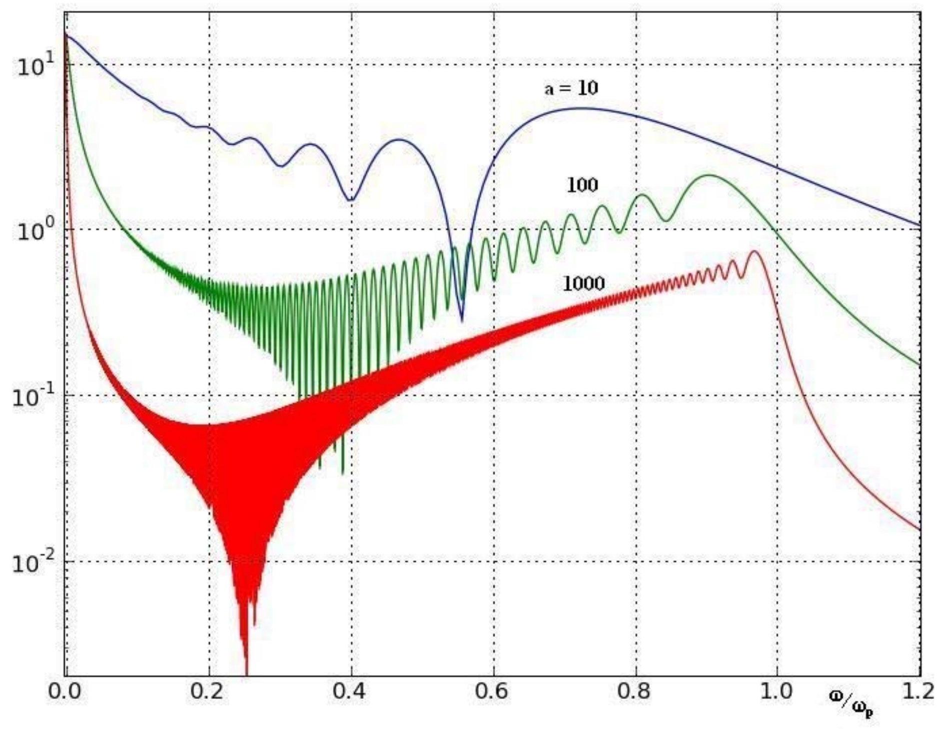


Electron excursion vs. time



Power radiated vs time

Radiation Spectrum



$$a = \frac{\omega_{p0} r_0}{c_s}$$

Ratio of plasma period to expansion time

Other Mechanisms

Direct current pickup on exposed conductors

$$\Delta q = 10^{-2}(m)\left(\frac{v}{3000}\right)^{2.6}$$

Electrostatic discharges

$C \approx$ 0.1 – 1.0 nF

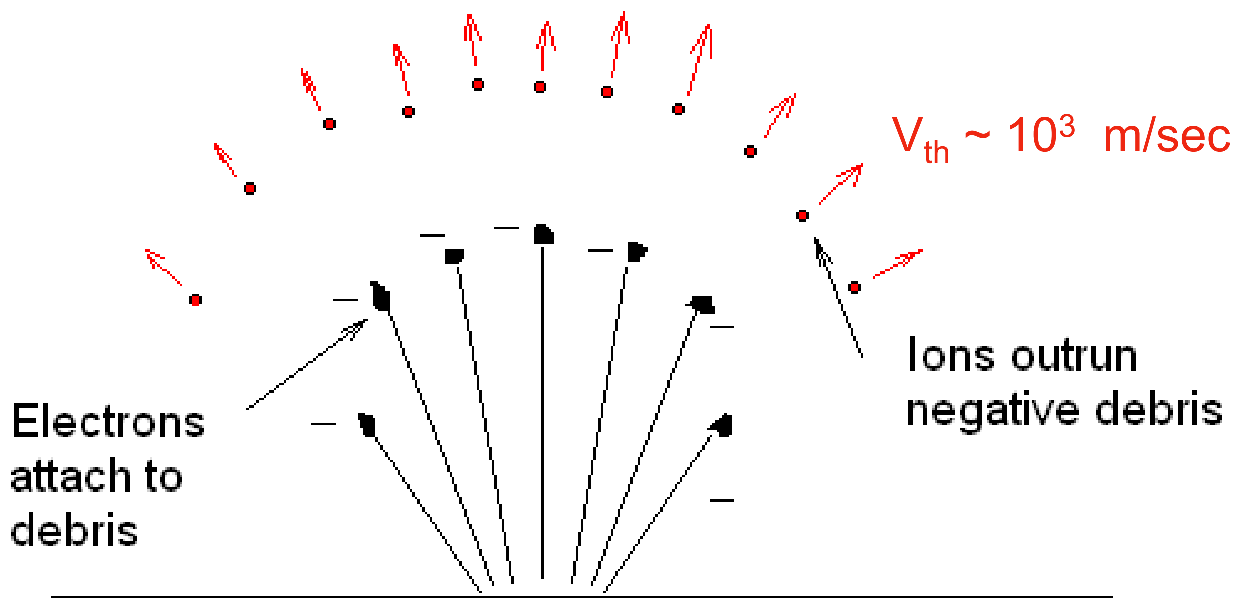
$\frac{1}{2} CV^2 \approx$ 0.01 – 0.1 J

Embedded dielectrics ?

However, spacecraft charging may augment meteoroid plasma Formation. Little is known on this topic.

Charge separation caused by impact debris: Triboelectric effect

Charge separation can result in small breakdown events or transient currents due to differential thermal velocities



EMP spectrum peaked at low frequencies ~ v_{th}/L

Proposed Experiment

Objective: Develop a concept for an in-situ meteoroid EMP detector
Design sensors to measure the following:

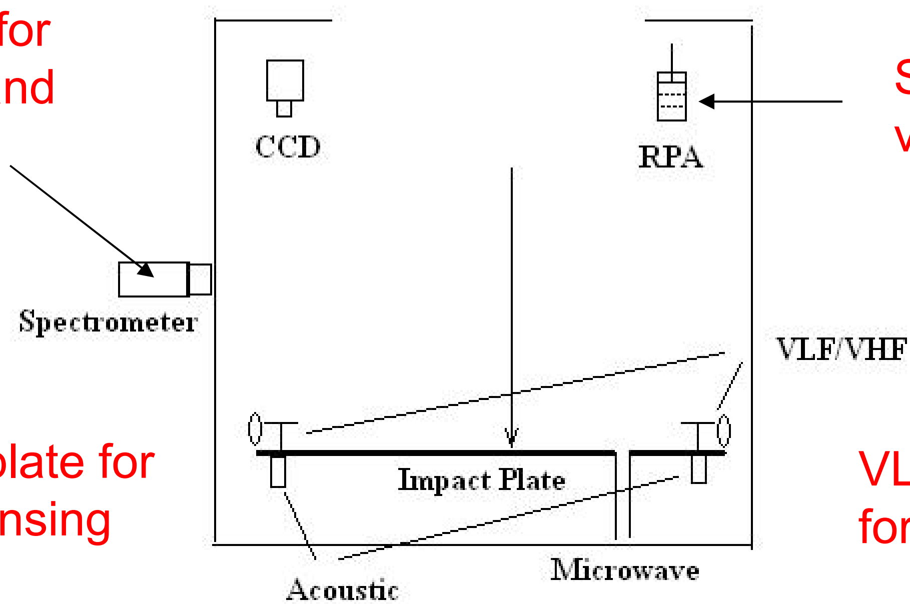
- EMP:
  - Power as a function of distance from impact
  - Power as a function of frequency spectrum
- Plasma density
- Plasma temperature
- ESD vs. EMP characteristics
- Spacecraft charging
- Optical radiation
- Infrared
- Meteoroid properties:
  - Mass
  - Velocity
  - Mass flux

Sensor Concept

CCD imager

Spectrometer for Temperature and composition

Scanning RPA for velocity



Multi-layered plate for penetration sensing

VLF/VHF sensors for EMP

Acoustic sensors for intensity and location

Microwave aperture sensor

All diagnostic techniques need to be qualified experimentally.